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GRD RESEARCH NOTES
No. 73

ACCURACY OF DENSITY FROM THE ROBIN FALLING SPHERE

Robert Leviton
John B. Wright

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Project 6670
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Meteorological Development Laboratory
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Bedford, Massachusetts

Abstract

Atmospheric density from about 200, 000 ft down to 100, 000 ft can be obtained by radar track of the ROBIN sphere as it falls toward the ground. An analysis is made of the various sources of error in the system including the equations of motion, drag-coefficient evaluation, radar-position data, and computational techniques to determine their effect on the accuracy of the calculated densities. Some ROBIN density data are presented.

Acknowledgments

The contents of this Geophysics Research Note were first presented at the American Meteorological Society Session of the 16th Annual Conference of the Instrument Society of America, Los Angeles, California, 11 September 1961.

The writers gratefully acknowledge the contribution of Mr. Nicholas Engler of the University of Dayton Research Institute who is responsible for the development of computer program for reduction of ROBIN data under a GRD contract.

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ACCURACY OF DENSITY FROM THE ROBIN FALLING SPHERE

1. Introduction

The ROBIN (Rocket Balloon Instrument) falling sphere is a small, super-pressured, plastic balloon developed by the Air Force Cambridge Research Laboratories to meet an Air Force requirement for a reliable, simple, and low-cost operational method of sounding the atmosphere. The nonmechanical, nonelectronic ROBIN provides a means of obtaining information on meteorological parameters above rawinsonde balloon levels to a height of at least 60 km (200, 000 ft).

Primarily developed as a payload for the ARCAS sounding rocket, the ROBIN sphere has also been ejected from a LOKI rocket and conceivably could be compatible with other small meteorological rockets either being developed or proposed. The sphere (Fig. 1) is one meter in diameter, is fabricated of 1/2-mil mylar and has a built-in, aluminized 1/4-mil mylar corner reflector. After ejection from the rocket at a height of about 70 km, the sphere is inflated to a super-pressure of 10-12 mb by vaporization of 35 cc of isopentane which is carried within it in a small capsule. Radar is then used to track the falling ROBIN and space position data thus obtained can be reduced to the desired parameters. This paper deals with the accuracy of density data obtainable from the ROBIN falling sphere. However, in addition to density, the technique is capable of producing excellent wind data, as well as temperature and pressure information which can be calculated from the computed densities using the hydrostatic and perfect gas law equations.

To date, over 200 shots have been made at Cape Canaveral, Wallops Island, Eglin AFB and Holloman AFB with balloon acquisition on about 90 percent of the flights and useable data on 80 percent. The sea-level launches averaged about 75 km in height while altitudes of the order of 90 km or better were obtained on some of the shots at Holloman, which is about 4000 ft above sea level. Data reduction is being accomplished by the University of Dayton Research Institute, who have also contributed a good part of the error analysis used in this paper.

Figure 1. Robin Balloon

2. Equations of Motion

The motion of a body as it falls earthward may be described by using the equations for drag, weight, and other forces. Solution of motion in the vertical direction (neglecting Coriolis effect) gives the equation for the density of the atmosphere:

$$\rho = -\frac{m(\ddot{Z} + g)}{V_L\, g - 1/2\, C_D\, A\, V\, \dot{Z}} \tag{1}$$

The total velocity, V, which the balloon "feels" is evaluated by the relationship:

$$V = \sqrt{(\dot{X}-Wx)^2 + (\dot{Y}-Wy)^2 + (\dot{Z}-\dot{W}z)^2} \tag{2}$$

Equation 2 can be expanded to include measurable terms of horizontal and vertical acceleration:

$$V = \sqrt{\left(\frac{m\ddot{X}\dot{Z}}{m(\ddot{Z}+g)-\rho V_L g}\right)^2 + \left(\frac{m\ddot{Y}\dot{Z}}{m(\ddot{Z}+g)-\rho V_L g}\right)^2 + \dot{Z}^2} \tag{3}$$

where Wz is assumed equal to zero.

3. Sources of Error

An examination of the density equation (Eq. 1) shows that the accuracy of any calculated density data depends on the accuracy of the value of drag coefficient used, the accuracy of the measurement of fall velocity and acceleration, and the tolerance to which the sphere is fabricated. In the following discussion, it should be borne in mind that in order to fully evaluate the system errors a technique was used which will turn out to be somewhat more sophisticated than the eventual field operational method. Data in the form of azimuth and elevation angles and slant range were obtained from the AN/FPS-16 radars as a function of time. Errors expressed are so-called standard (one sigma) values.

DRAG COEFFICIENT

The fall velocity, $\dot{Z}$, which is essentially V except in regions of strong wind shear, is shown in Fig. 2. A range of velocities is possible at any altitude following the attainment of terminal velocities because of the varying balloon weights and variations in atmospheric density. The drag coefficient of a sphere subjected to motion through a gas can be shown to be a function of Mach and Reynolds Numbers rather than velocity.

$$M = \frac{V}{a} = \frac{V}{K_1\sqrt{T}} \tag{4}$$

$$R = \frac{\rho V d}{\mu} = \frac{\rho V d(T+K_3)}{K_2\ T^{3/2}} \tag{5}$$

These two parameters, according to dimensional analysis and aerodynamics, define conditions which if duplicated in model testing will assure similarity to full-scale conditions. Figure 3 shows the Mach and Reynolds number ranges of the ROBIN balloon.

Wind tunnel tests to evaluate the drag coefficient of the ROBIN sphere were necessary for various Mach and Reynolds numbers because no previous experimental work had been done for the ROBIN flow conditions. Accordingly, tests of small spheres of 3/4 in. to 2 in. diameters were performed over a range of Mach Numbers (0. 79 and below) and Reynolds Numbers in the high-speed, variable-density wind-tunnel of the University of Minnesota by Dr. Helmut G. Heinrich. The preliminary drag coefficients thus obtained and used in the density calculations appear in Fig. 4.

An analysis of the over-all accuracy of the test equipment including all pressure gages and optical instruments yields rms errors in drag coefficient ranging from 2 percent at high altitude to 1 percent at low altitude conditions.

The computation of density involves a reiterative process because the drag coefficient must be obtained as a function of M and R that are in turn functions of density and temperature, both unknowns. Therefore, starting at the highest altitude point, an assumption is made that the pressure corresponds to that of the 1959 ARDC Standard Atmosphere. Thus an unknown error is introduced into both temperature and pressure at the highest point. If, for example, the temperature is 10 percent in error, the drag coefficient selected may be 6-1/2 percent in error due to incorrectly calculated M and R values. However, for succeeding points decreasing in altitude, the pressure is calculated using the hydrostatic equation; the error, while still included as a constant amount, decreases in percentage. If the above error of 10 percent occurs at 70 km, the corresponding error turns out to be only 2-1/2 percent at 60 km in both temperature and pressure. The corresponding drag-coefficient error is then about 2 percent. Hence it would appear that perhaps the top 10 to 15 km of density profile is subject to larger error than experienced below this point. If data are not reported until 60 km, although the sphere is ejected at a higher altitude and calculations begun, this assumption of a standard T and P does not result in too significant an error. The total drag error, assuming a pressure and temperature error of 10 percent at 70 km, can be said to approach 3 percent at 60 km while still only 1-1/2 percent at 50 km and 1 percent at 30 km.

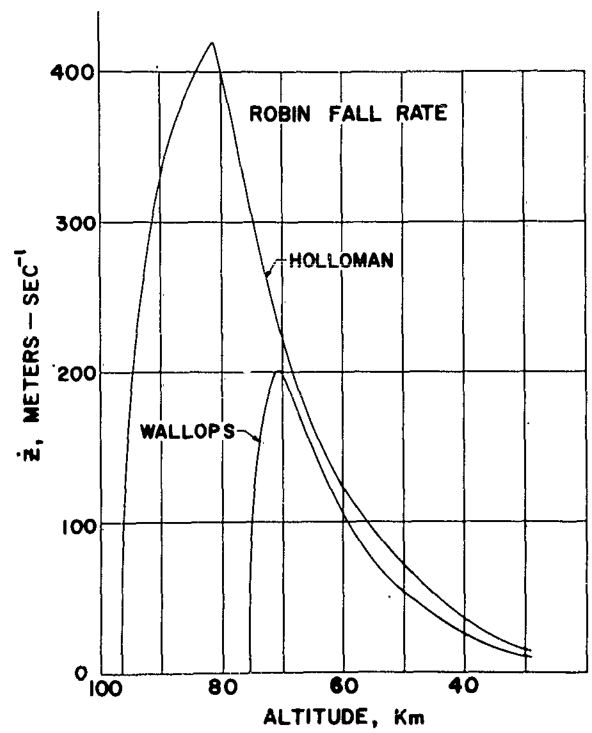

Figure 2. Typical Examples of ROBIN Fall Velocity

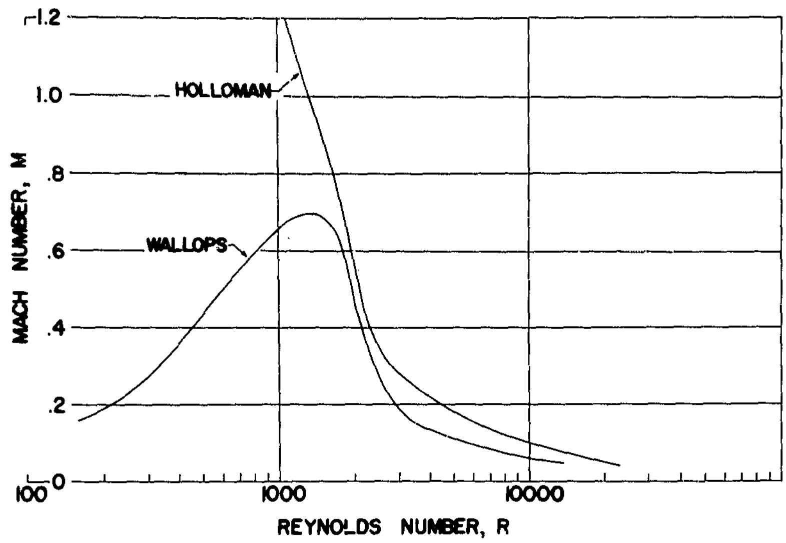

Figure 3. Typical ROBIN Fall Conditions Expressed in Mach and Reynolds Numbers

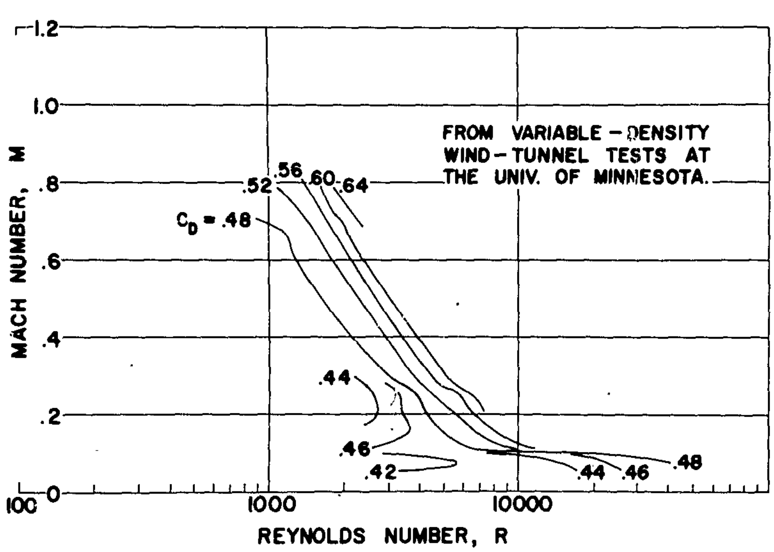

Figure 4. Drag Coefficients of a Sphere

VELOCITY AND ACCELERATION

The evaluation of the velocity and acceleration terms has been the subject of considerable study and experimentation by the University of Dayton Research Institute. A technique of curve-fitting has been evolved which, it is believed, will smooth out noise but will not eliminate real variations. For each of the X, Y, and Z coordinates, the method involves a least-square fit using orthogonal polynomials. Thirty-one half-second data points are fitted to evaluate a space position and the slope or velocity at the mid-point. Two of these points are then dropped and two additional selected at the lower-altitude end to repeat the process at a mid-point one second later. Accelerations are obtained by straight-line smoothing of seven velocity points at a time.

Consideration of error in the velocity and acceleration terms has been made by evaluating the sample variance of some shots from the equations used in smoothing. Comparison then with the theoretical variance due to radar error (angles ± 0.1-mil and slant range ± 5 yards rms error) indicates that the sample variance is in the same order of magnitude as the theoretical, or that errors due to smoothing are minimized. The errors due to radar, smoothing, and all data handling sources are thus included in the sample variances. The errors are briefly summed below:

		Percent of Error	
Term	Error, Absolute	Altitude, 60 km	Altitude, 30 km
$\dot{Z}$, V	0.2 m/sec	0.13 of 1%	1.3%
$\ddot{Z}$	0.05 m/sec^2	0.5 of 1% of term	$(\ddot{Z} + g)$

PHYSICAL DIMENSIONS AND GRAVITY

Various dimensional properties of the balloon are maintained by manufacturing tolerances and inspection. The weight, for example, is measured to within 0.5 gram. Diameter tolerance is 0.5 of 1 percent. Thus manufacturing errors lead to a mass-to-area ratio that is known within 0.8 of 1 percent on a standard error analysis basis.

The acceleration due to gravity, g, is corrected for both latitude and altitude in the computations. For all practical purposes the error in g can be treated as negligible.

OTHER TERMS

The Coriolis effect is so small ($\ddot{C}_{f_z}$ = 0.1 of 1% of $\ddot{Z}$) that it is not considered in this analysis.

The maximum value of the buoyancy term, $V_L g$, is in the order of 5 percent of the other group of terms in the denominator of Eq. (1) at the lowest altitude and even smaller at higher altitudes. Therefore, any small error would be negligible in the total effect on density, and it too can be ignored in the over-all error evaluation.

SUMMARY OF ERRORS

In summarizing the errors associated with the ROBIN density calculation, it can be seen that the total rms error at 60 km is essentially that of the estimated drag-coefficient error or 3 percent. At the lower levels rms evaluation of the various errors (velocity, acceleration, dimensional, and drag) turn out to be about 2 percent.

In the preceding discussion the assumption was made that vertical winds are nonexistant. If, however, a vertical wind of 0.5 m/sec is used in the density calculation, then the computed densities will be in error by about 4 percent at an altitude of 30 km and 2 percent at 40 km, with decreasing error in the higher levels. Admittedly, this would have a detrimental effect on system accuracy as it would also have on other sounding techniques which assume a zero vertical wind. A better assessment of this type of error must await further knowledge of vertical winds.

4. Data

Figure 5 shows two density profiles for two soundings made at Eglin AFB in Florida. Both show values somewhat below the standard. In shot No. 61 note the rapid increase in density at the lowest altitude; this may be due to collapse and streaming of the balloon with probable change in drag coefficient.

Figure 6 contains a magnified section of fine detail for another shot. The fluctuations are still under study but perhaps indicate either a damaged balloon, vertical winds, or that density actually goes through such fluctuations. Most interesting is the comparison of densities obtained using the data from two independent radars. Strong similarity in form and in magnitude can be seen between the two profiles shown in Fig. 6.

5. Conclusions

While the preceding analysis indicates the ROBIN technique is capable of determining atmospheric density from 60 km down to 30 km with an accuracy of 2 to 3 percent it should be stressed that this is so only with a high precision tracking radar and a sophisticated data reduction technique. The assumption is also made that the ROBIN sphere is fully inflated at all times. Experience has shown that occasionally an uninflated balloon is ejected and tracked. However, a

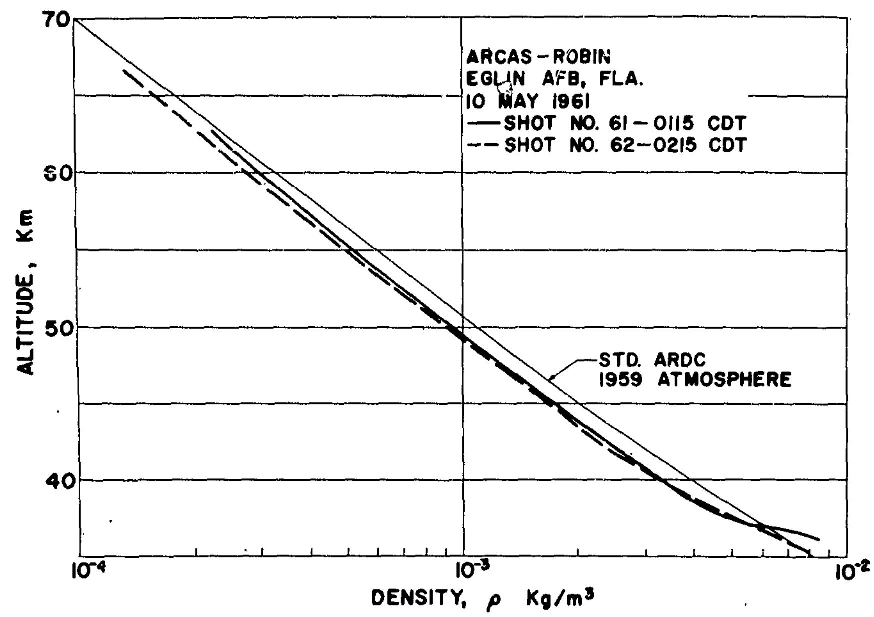

Figure 5. Two Typical Density Profiles

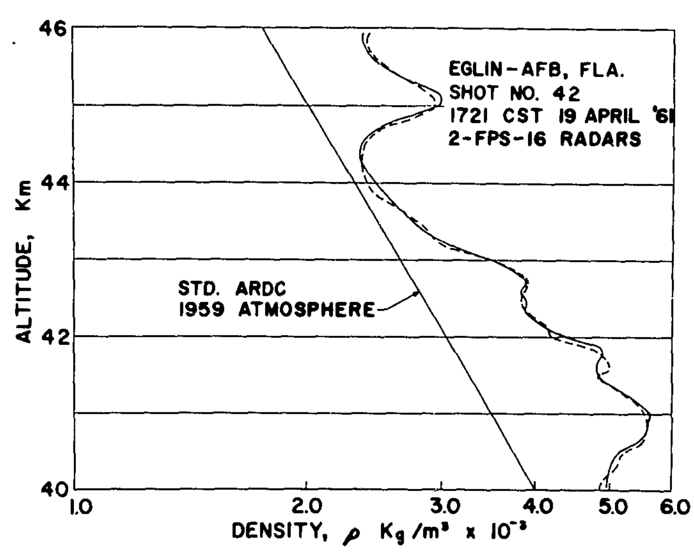

Figure 6. Density as Obtained from Independent Radars

simple method of recognizing such a malfunction from the radar information or data output is currently being investigated.

As mentioned previously, the feasibility of employing the ROBIN technique by using a lesser-type radar (such as the 10 cm Mod II or MSQ-1) and a much-simplified data reduction method for routine weather station usage is highly desirable and progress is being made in this direction. However, regardless of the outcome of this study, it appears that where useable (and this includes all missile ranges, at the least) the ROBIN system does have the capability of obtaining accurate density information on a routine basis. This is of extreme importance both to the meteorologist and the missile designer.

6. Nomenclature

$\dot{X}$ and $\dot{Y}$	=	horizontal components of balloon velocity relative to earth
$\ddot{X}$ and $\ddot{Y}$	=	horizontal components of balloon acceleration
W_x and W_y	=	horizontal components of wind
$\dot{Z}$	=	vertical balloon velocity relative to earth
$\ddot{Z}$	=	vertical balloon acceleration relative to earth
W_z	=	vertical wind, usually assumed equal to zero
V	=	total balloon velocity relative to air
T	=	atmospheric temperature, absolute
ρ	=	atmospheric density
a	=	speed of sound
μ	=	coefficient of viscosity
g	=	acceleration due to gravity
d	=	balloon diameter
A	=	cross-sectional area of balloon
V_L	=	volume of balloon
m	=	mass of balloon
K	=	various constants
C_D	=	drag coefficient of balloon
M	=	Mach Number
R	=	Reynolds Number

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